The Case for a Precision Higgs Program

S. Dawson , BNL

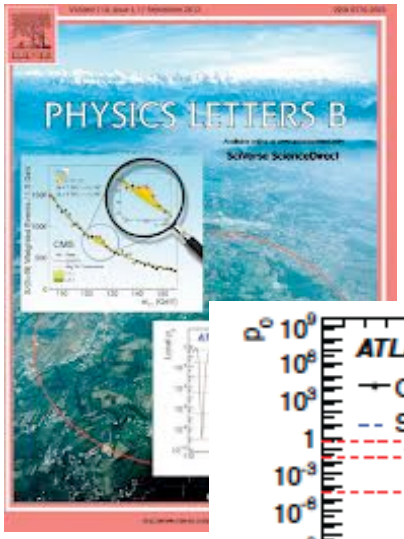
Higgs Working Group: SD, Andrei Gritsan, Heather Logan, Chris Tully (Chair), Rick van Kooten

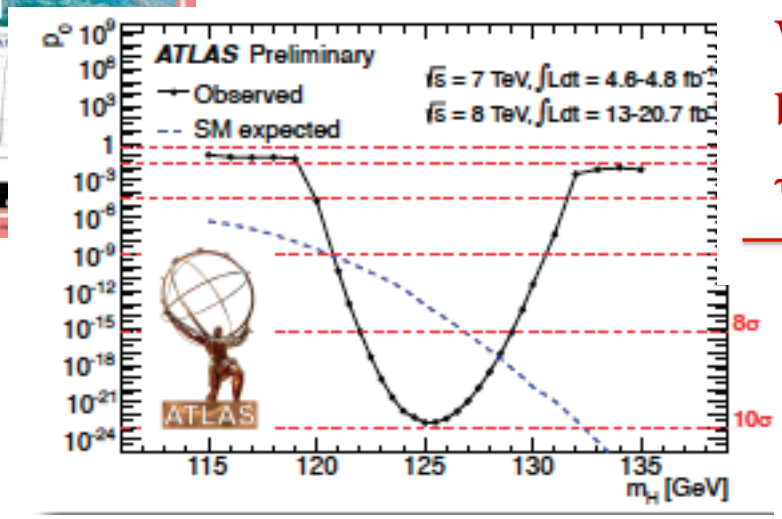
Snowmass on the Mississippi, Community Summer Study, 2013

THIS IS NOT A SUMMARY OF THE REPORT!!! I POINT OUT SOME OF THE OPPORTUNITIES AND CHALLENGES, ALONG WITH GENERAL FEATURES.

We discovered a Higgs boson!

- The minimal Higgs model is very predictive
- Only free parameter is M_h





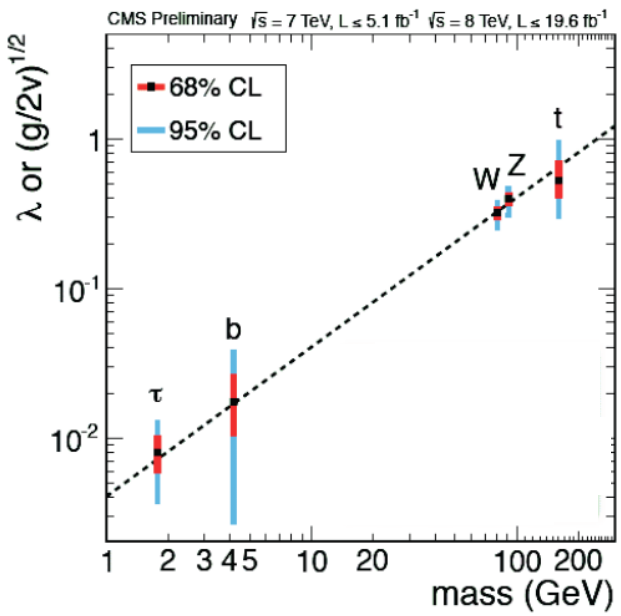
CMS

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

Both ATLAS and CMS have close to 10σ significance

All Higgs Couplings predicted in SM

- Very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to (mass)^2
  - Higgs self-couplings proportional to M_h^2



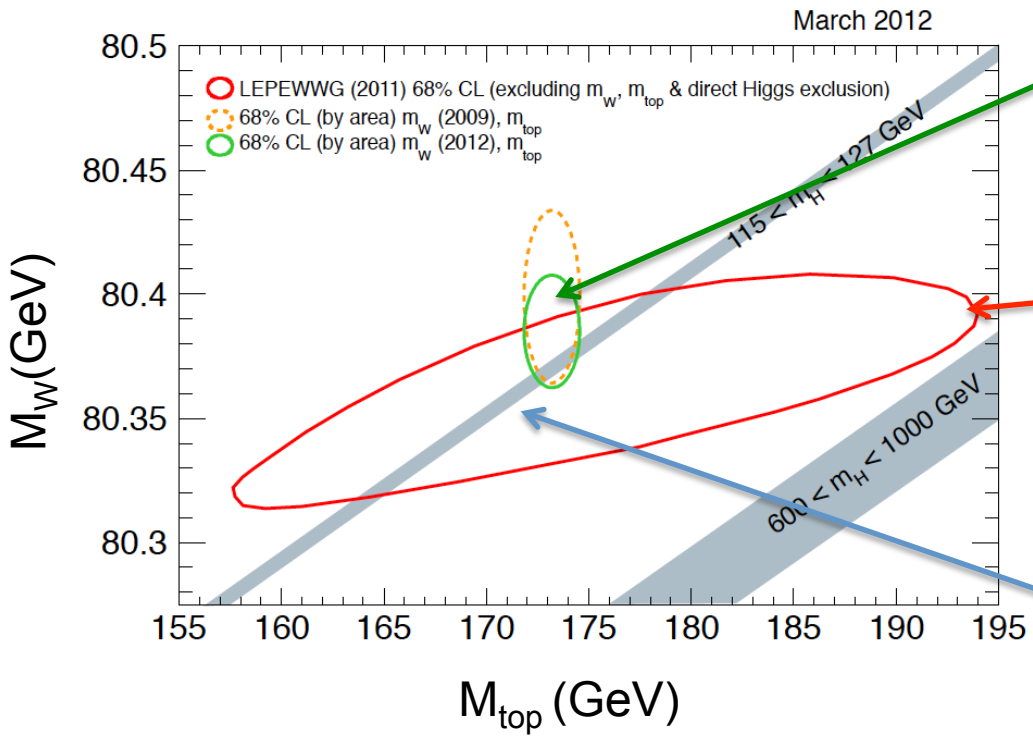
If couplings didn't have this pattern, it would indicate that not all mass comes from a single Higgs boson

Need Something like a Higgs

- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W and Z gauge bosons
  - Non-zero mass of fermions
  - Unitarity conservation at 1 TeV
- Precision electroweak data is consistent with SM

So the fact that the observed Higgs-like particle looks ***SM-like*** is no surprise

Precision Physics Before Higgs Discovery



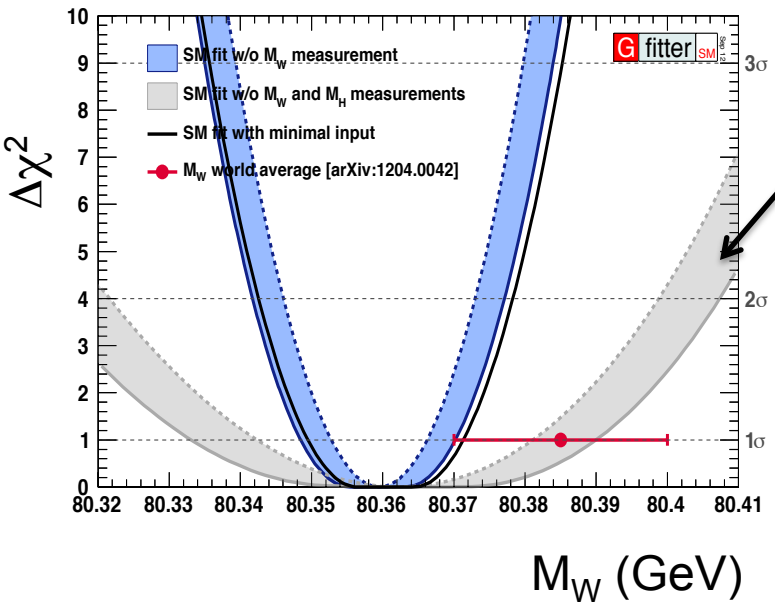
Experimental measurements from Fermilab

Inferred values of M_W and M_t from other experiments

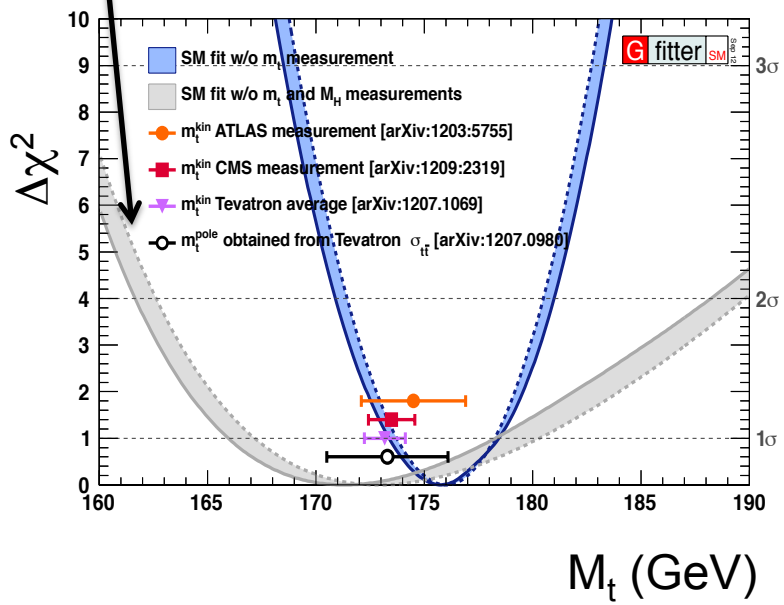
Theory predictions

Self-consistency of the theory told us the Higgs couldn't be too heavy without new physics

Precision Physics After Higgs Discovery



Fit without Higgs



The SM as an effective low energy theory is an extremely good approximation

The Higgs Frontier

- What have we found ?
  - Is it ***THE*** Higgs?
- What's next ?
  - Are there more Higgs particles?
  - Is there a next energy scale?

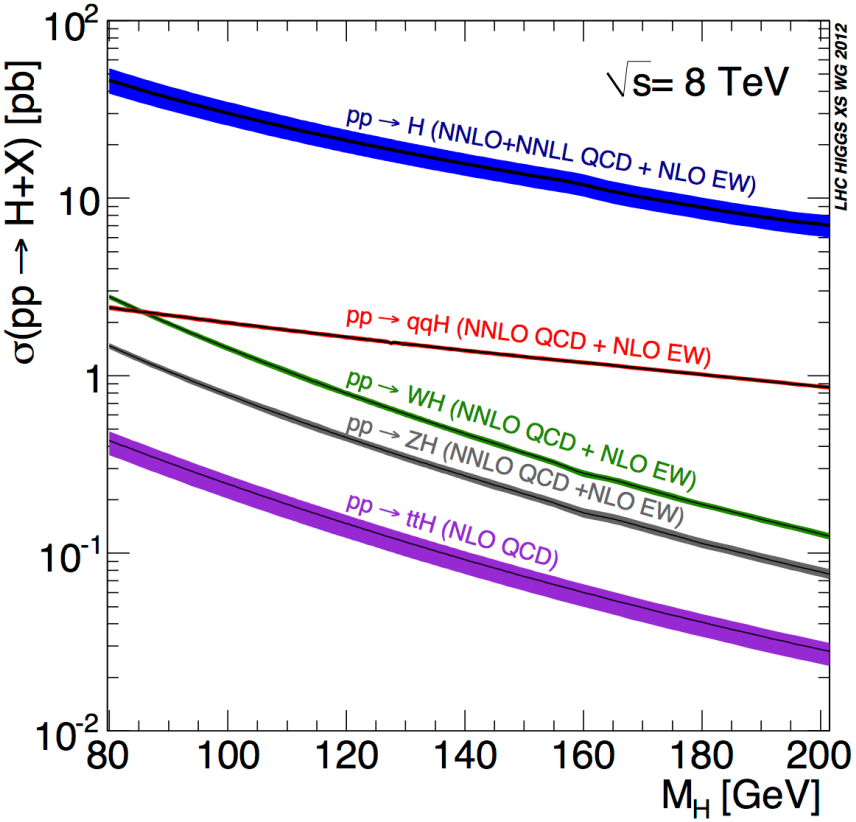
What are the important measurements/calculations to help us answer these questions?

The Future Precision Higgs Program

- Higgs Properties
  - Mass/width
  - Spin-parity
  - Couplings
- Search for new Higgs-like particles
- Naturalness? The next scale?
  - Often connected with new particles/Non-SM couplings

We are entering the next discovery phase of Higgs physics

Precision Predictions at the LHC



NLO predictions now in MC programs, POWHEG, aMC@NLO

$$\sqrt{s} = 8\ TeV, M_H = 126\ GeV$$

$$\sigma_{gg} = 19^{+7.2\%+7.5\%}_{-7.8\%-6.9\%}\ pb$$

QCD Scale PDF+α_s

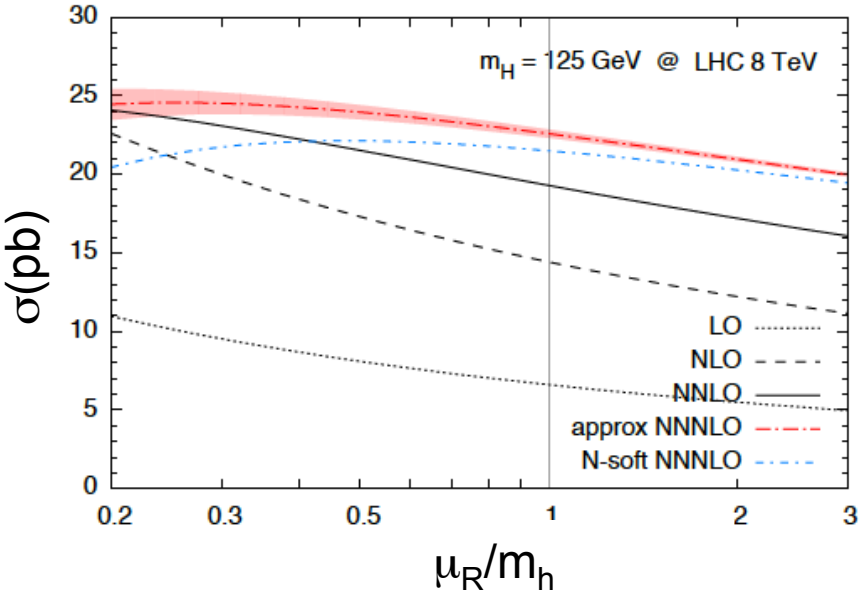
Theory uncertainties affect ability to extract couplings at LHC

[LHC Higgs Cross Section Working Group]

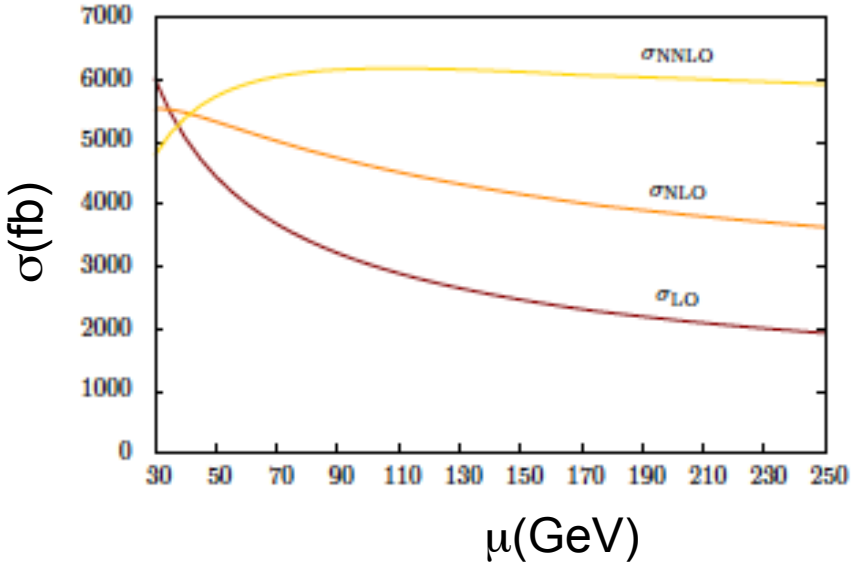
H+jet @NNLO, H@NNNLO

- Will decrease errors from scale uncertainty and jet binning

Higgs inclusive cross section



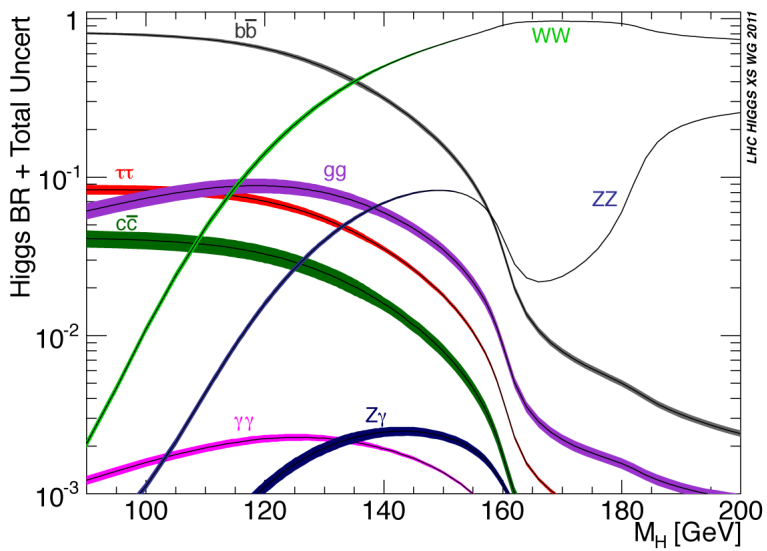
Higgs+jet at √s=8 TeV



Rates are increased with new results

[Ball et al, 1303.3590; Boughezal et al, 1302.6216]

Theory Predictions on Branching Ratios



- Parametric uncertainties can be reduced by better determination of m_b (lattice?)
- Theory uncertainties from missing EW corrections will be reduced

Target: Reduce theory uncertainties to ~1% to correspond to 1% measurements at lepton colliders

Decay	Theory Uncertainty (%)	Parametric Uncertainty (%)	Total Uncertainty on Branching Ratios (%)
$H \to \gamma\gamma$	± 2.7	± 2.2	± 4.9
$H \to b\bar{b}$	± 1.5	± 1.9	± 3.3
$H \to \tau^+\tau^-$	± 3.5	± 2.1	± 5.6
$H \to WW^*$	± 2.0	± 2.2	± 4.1
$H \to ZZ^*$	± 2.0	± 2.2	± 4.2

[LHC Higgs cross section working group]

Testing Higgs Couplings

- Assume 1 resonance/zero width approx/no new tensor structures

$$\sigma \cdot BR(ii \to h \to jj) = \frac{\sigma_{ii}\Gamma_{jj}}{\Gamma_h}$$

- Define scaling factors κ

$$\mu(gg \to h \to \tau^+\tau^-) = \frac{\sigma(gg \to h \to \tau^+\tau^-)}{\sigma(gg \to h \to \tau^+\tau^-)\,|_{SM}} = \frac{\kappa_g^2\kappa_\tau^2}{\kappa_h^2}$$

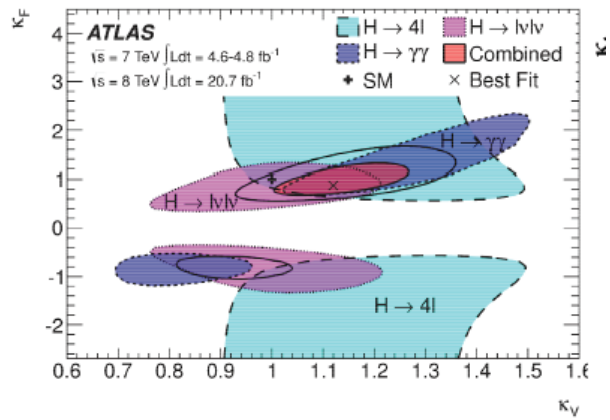
- Approaches to loops: κ_γ, κ_g can be
  - Written as function of SM scaling factors: eg $\kappa_g=\kappa_g(\kappa_t,\kappa_b)$
  - Treated as free parameters to look for BSM contributions
- Current fits have assumptions about Γ_h

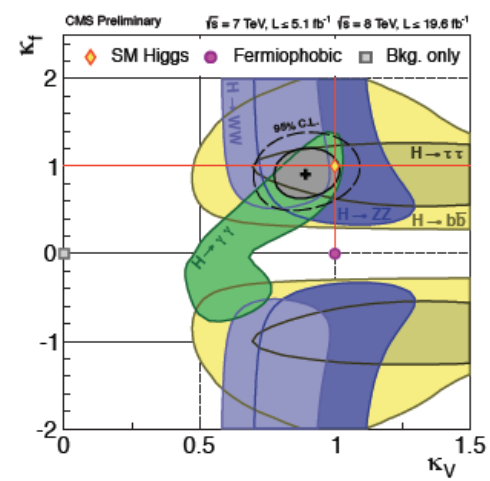
All μ and κ experimentally consistent with 1

[LHC Higgs Cross Section Working group, arXiv1307.1346]

Degeneracy in Couplings: $\sigma_{ii\to h\to jj} \sim \frac{\kappa_i^2 \kappa_j^2}{\Gamma_h}$

- Higgs rates invariant under coupling scaling:
  - $\kappa \to \zeta\kappa$, $\Gamma_h \to \zeta^4 \Gamma_h$
- Assume (for example):
  - Fermion couplings scale as κ_F
  - W,Z couplings scale as κ_V
  - No BSM contributions to Γ_h



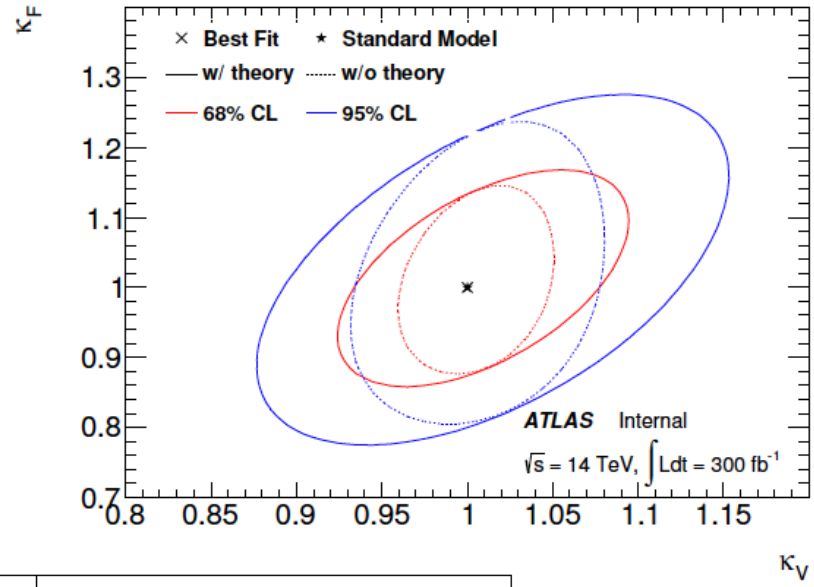


Currently 10-20% accuracy on coupling measurements

Plenty of room for new physics

Theory Uncertainty Matters

ATLAS Projections:



Coupling	With theory systematics	Without theory systematics
300 fb^{-1}		
κ_V	$^{+5.9\%}_{-5.4\%}$	$^{+3.0\%}_{-3.0\%}$
κ_F	$^{+10.6\%}_{-9.9\%}$	$^{+9.1\%}_{-8.6\%}$
3000 fb^{-1}		
κ_V	$^{+4.6\%}_{-4.3\%}$	$^{+1.9\%}_{-1.9\%}$
κ_F	$^{+6.1\%}_{-5.7\%}$	$^{+3.6\%}_{-3.6\%}$

~5-10% measurements

[ATLAS, Snowmass white paper]

Projections at the LHC

- CMS
  - Scenario 1: No improvements in systematics
  - Scenario 2: Systematics scale by 1/√L, theory error halved

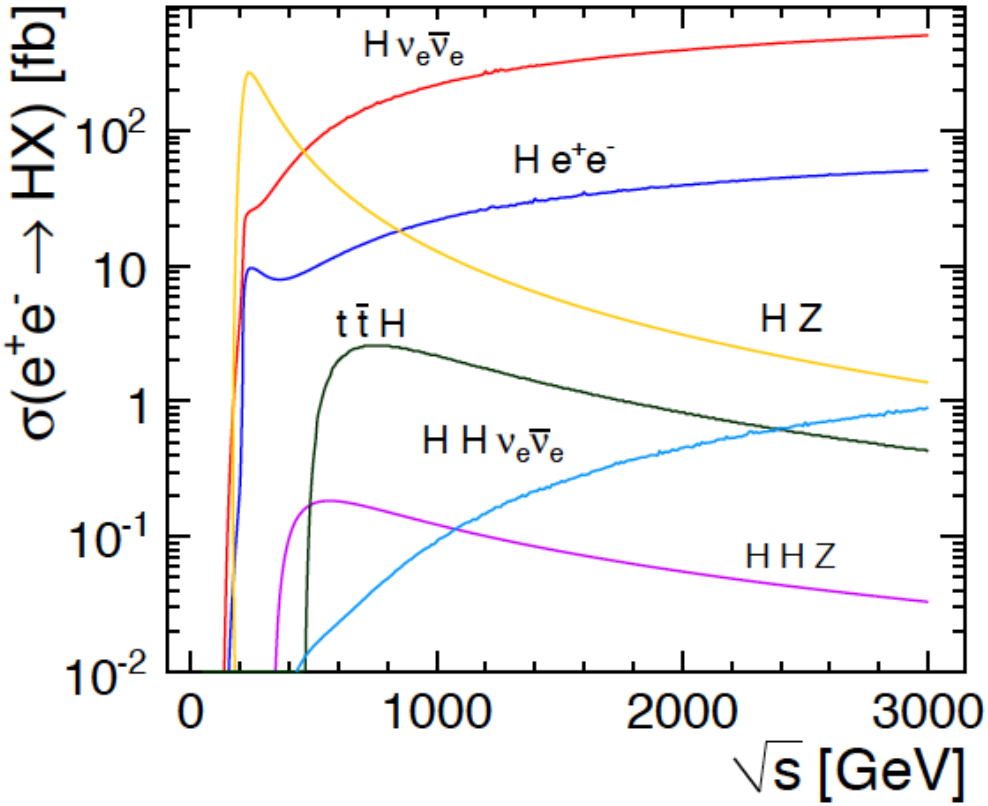
$L\,(fb^{-1})$	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$	$H \to \tau\tau$	$H \to Z\gamma$	$H \to$ inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

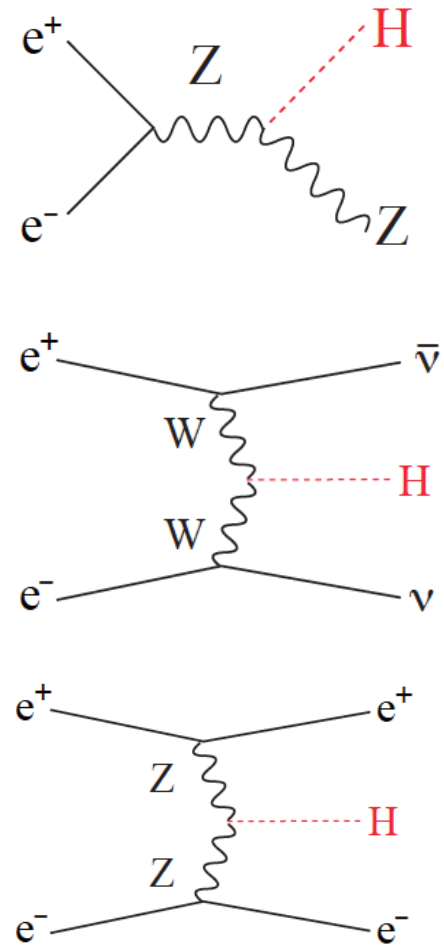
- LHC has sensitivity to Br_{inv} through ZH production, H→ invisible

- Current LHC limits at 95% cl: BR(H→ invisible) < 75%

[CMS Snowmass white paper, arXiv:1307.7135]

e^+e^- Colliders





Couplings at e^+e^- Colliders

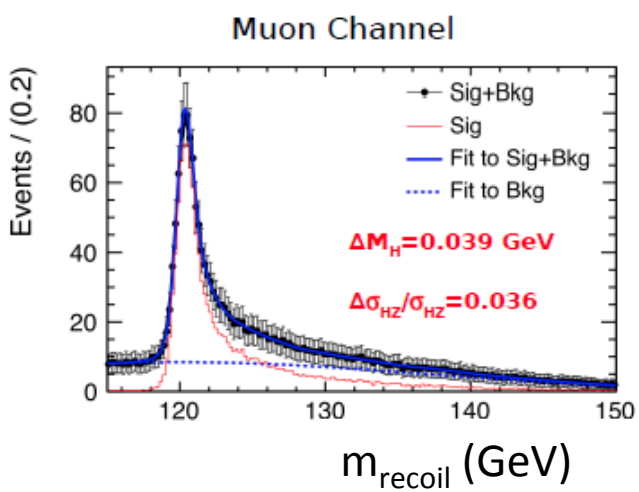
- Use recoil technique: $e^+e^- \to Zh$; tag $Z \to \mu^+\mu^-, e^+e^-$
  - Reconstruct recoil mass, $m^2_{\rm recoil} = (\sqrt{s} - E_{l^+l^-})^2 - |\vec{p}_{ll}|^2$
  - Identify Higgs independent of decay
  - This gives: $\sigma(Zh) \sim (g_{hZZ})^2$
  - Classify the rest of the events to measure BR ($h \to XX$)

ILC250:

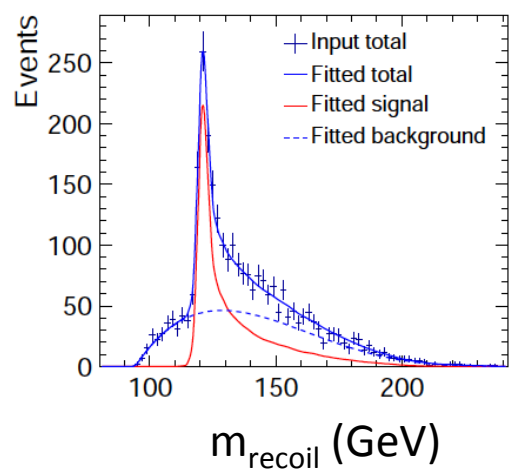
$$\frac{\Delta\sigma}{\sigma} = 2.5\%$$

$$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 1.3\%$$

$$\Delta\Gamma_h = 11\%$$



$e^+e^- \to Zh$, ILC at $\sqrt{s}$=250 GeV, 250 fb^{-1}



$e^+e^- \to Zh$, CLIC at $\sqrt{s}$=350 GeV, 500 fb^{-1}

CLIC350:

$$\frac{\Delta\sigma}{\sigma} = 4\%$$

$$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 2\%$$

Couplings at e^+e^- Colliders

- Recoil technique gives independent measurements of total width and branching ratios

- Get total Higgs width: $\Gamma_h = \frac{\Gamma(h \to ZZ)}{BR(h \to ZZ)} \sim \frac{\sigma(Zh)}{BR(h \to ZZ)}$

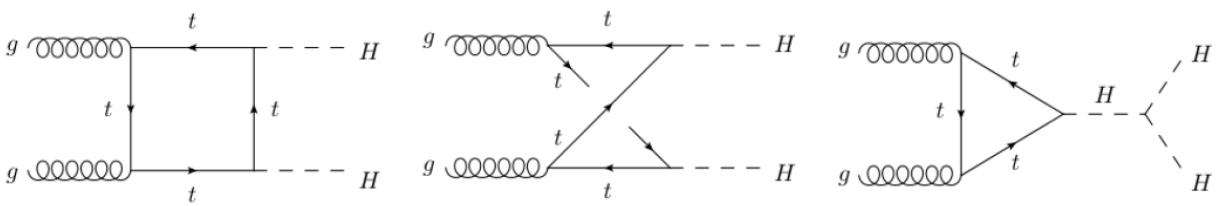
- At higher energies can also use $e^+e^- \to \nu\nu h$

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

Advantage: Coupling extractions don't need assumptions about total width

Discussion of Higgs Couplings, Wednesday, 8:30-10:00 am, Higgs Working Group

Higgs from SM Potential?



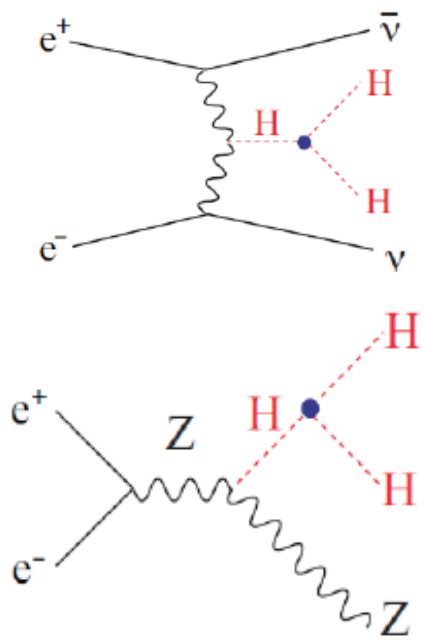
$$\text{SM:} \quad \lambda_{hhh} = \frac{3M_h^2}{v}$$

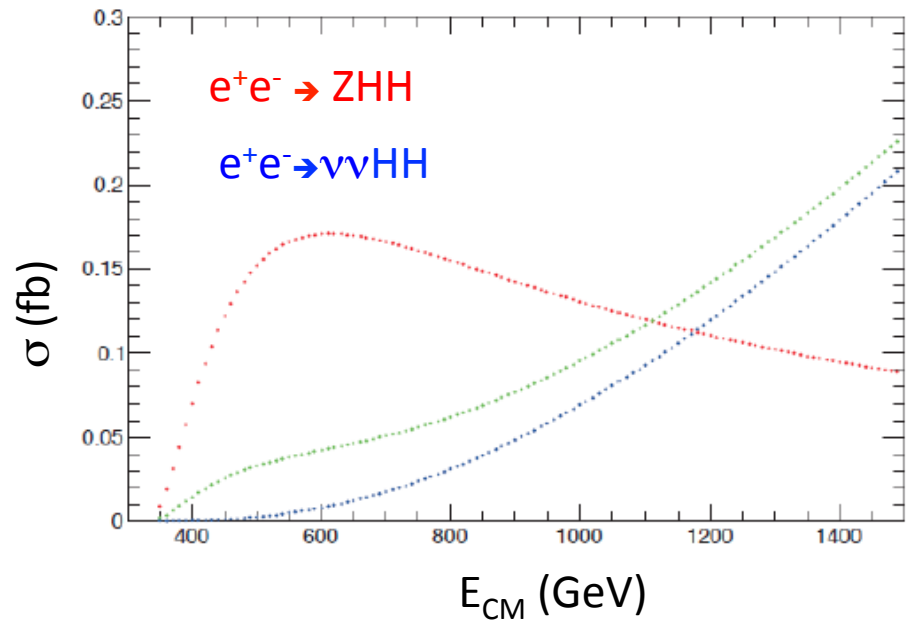
- Sensitive to hhh coupling and new particles in loops
  - Cancellation between box and triangle reduces sensitivity
  - Composite Higgs models can increase rate by ~ factor of 2
  - Probes non-SM $t\bar{t}hh$ couplings
- Small rate: 3 fb at 8 TeV, 15 fb at 14 TeV
  - bb$\gamma\gamma$ gives 3σ with 3 ab^{-1} (270 events with 3 ab^{-1})
  - 50% measurement of λ_{hhh} at LHC per experiment

[ATLAS/CMS HL-LHC study]

Double Higgs production in e^+e^-

- Low rates: 400 events at 500 GeV, 1000 events at 3 TeV
- Large backgrounds





$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}} \sim 25\%(ILC1000),\ 15\%(CLIC)$$

Discussion of double Higgs production: Friday, 8:30-10:00 am, Higgs Working Group

How well do we *NEED* to measure Higgs Couplings?

- LHC measures $\sigma \cdot$BR (products of couplings)
- e^+e^- uses recoil method for model independence

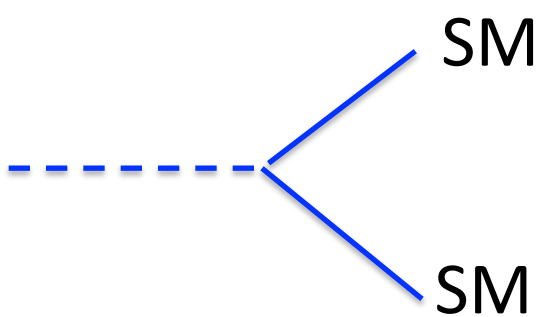
0th order answer: We found a new particle which we hypothesize is the quanta of EWSB. We want to measure couplings as precisely as possible

1st order answer: Let's see what kind of deviations we might expect in reasonable scenarios

- To be sensitive to deviation Δ, need to measure to $\Delta/3$ or $\Delta/5$

Many Reasons to have more than 1 Higgs

- Models to explain dark matter, flavor often have more than 1 Higgs boson
  - Simple example: SM Higgs mixed with electroweak singlet, S



Coupling to light Higgs, h ~ $\cos\theta$
Coupling to heavy Higgs, H ~ $\sin\theta$

- Universal rescaling of Higgs couplings, $\kappa_F = \kappa_V = \cos\theta$

Complementarity of Approaches

- Find the heavier Higgs and/or measure deviations in couplings
- What is largest sin θ such that we won't see H (heavier Higgs) at LHC with 100 fb^{-1}?
  - For M_H=1.1 TeV expect 13 signal events, 7 background ($S/\sqrt{B}$~5)
  - To see new physics (without observing H) need $(\sin\theta)^2 < .12$

Target precision: $\delta\kappa \sim -\frac{\sin^2\theta}{2} \sim -6\%$

[Gupta, Rzehak, Wells]

Two Higgs Doublets

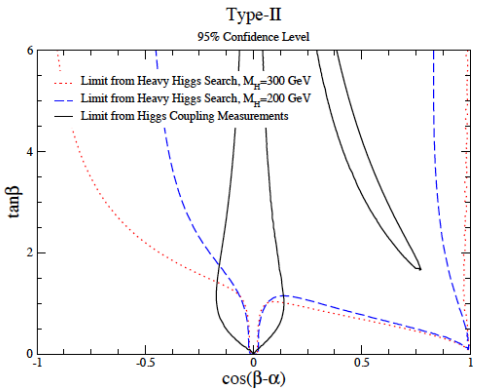
- Many models have extended Higgs sectors
  - Two Higgs doublet models can be used as effective theories for many of these models
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
  - 4 types of 2HDM models which avoid tree level FCNCs
  - Classified in terms of tan $\beta = v_2/v_1$, α, m_h

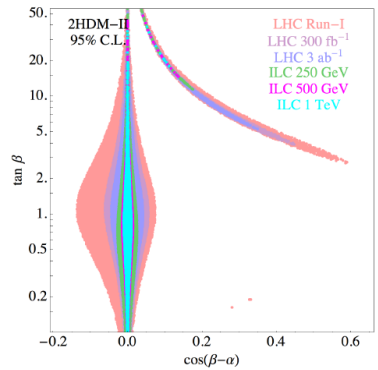
$$\sin 2\alpha = -\sin 2\beta \left(\frac{M_H^2 + m_h^2}{M_H^2 - m_h^2} \right)$$

  - Predictive models (MSSM is special case)

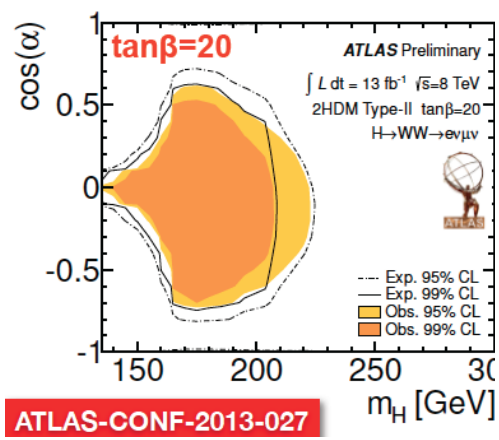
Complementarity in 2HDMs

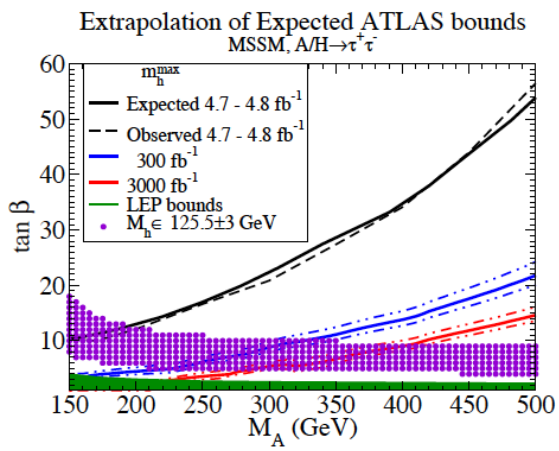
- Coupling fits vs direct search for H/A at LHC, e^+e^-, $\mu^+\mu^-$

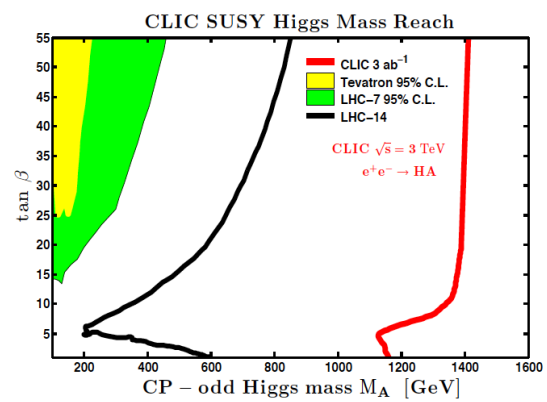




Direct search at e^+e^- typically reaches $M \sim E_{CM}/2$







Barger,1307.3676; Chen, 1305.1624; Lewis, 1308.xxxx

Decoupling Limit: Type II 2HDMs

Assume $M_H, M_{H+}, M_A >> M_Z$

Coupling shifts are typically small:

$$\delta\kappa_V = -\frac{2M_Z^4 \cot^2\beta}{M_A^4} \sim .1\% \left(\frac{600}{M_A}\right)^2$$

$$\delta\kappa_t = -\frac{2M_Z^2 \cot^2\beta}{M_A^2} \sim -5\% \cot^2\beta \left(\frac{600}{M_A}\right)^2$$

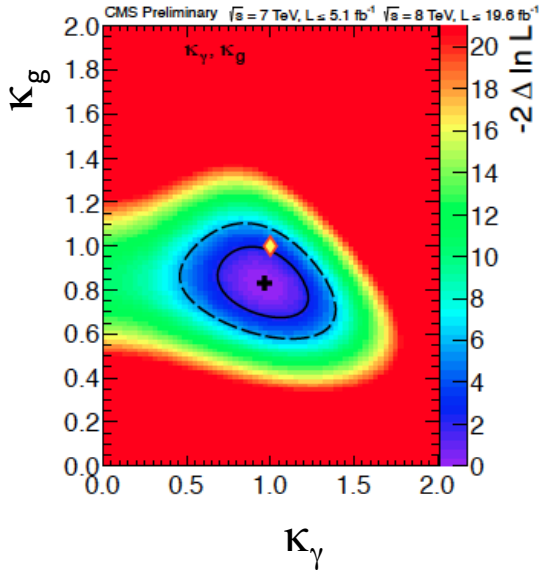
$$\delta\kappa_b = \frac{2M_Z^2}{M_A^2} \sim 5\% \left(\frac{600}{M_A}\right)^2$$

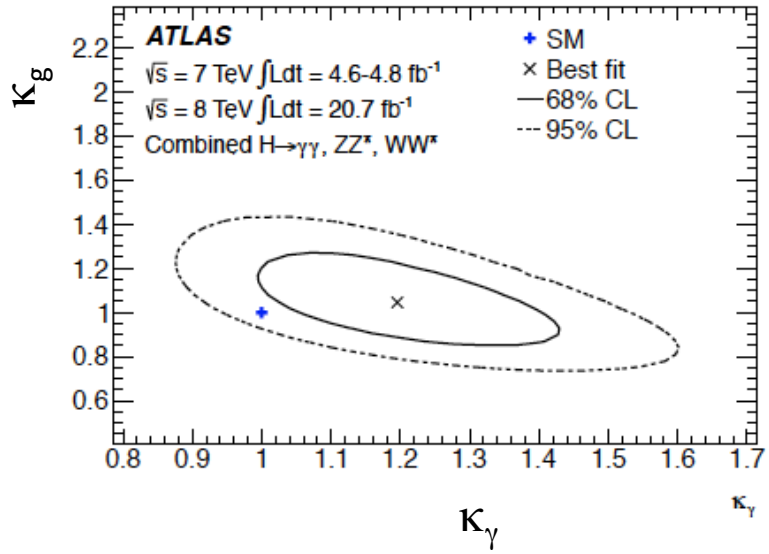
Target precision: $\delta\kappa < 5\%$

Coupling shifts depend on mass scale of new physics

Different models have different patterns of Higgs coupling shifts ➡ requires comprehensive set of measurements

Loop Induced Couplings





$$ATLAS : \kappa_g = 1.04 \pm 0.14 (68\% \text{ cl})$$

$$CMS : \kappa_g = [0.63, 1.05] (95\% \text{cl})$$

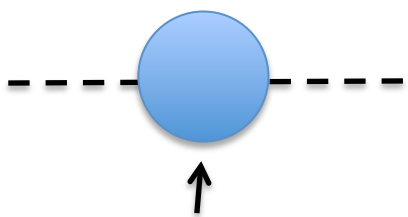
$$ATLAS : \kappa_\gamma = 1.20 \pm 0.15 (68\% \text{ cl})$$

$$CMS : \kappa_\gamma = [0.63, 1.3] (95\% \text{cl})$$

Compatible with SM predictions: Accuracy ~10-15%

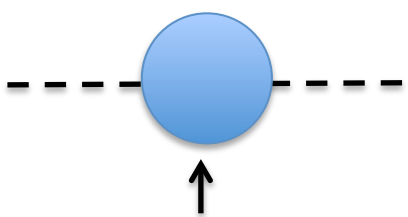
The Naturalness Connection

- Generically, solutions to naturalness involve new particles, which lead to deviations in Higgs couplings



SM particles

$$\delta M_H^2 \sim -(125\ GeV)^2 \left(\frac{\Lambda}{600\ GeV}\right)^2$$



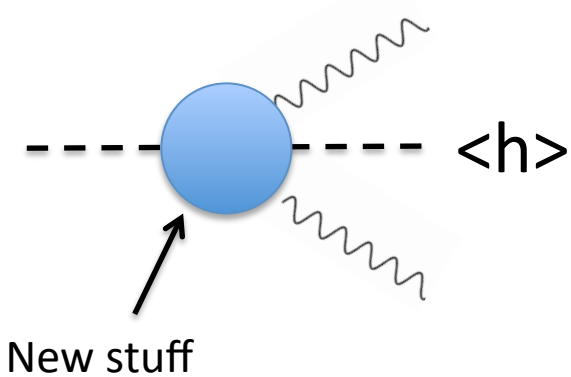
New stuff

$$\delta M_H^2 \sim +(125\ GeV)^2 \left(\frac{\Lambda}{M_{new}}\right)^2$$

For this cancellation to work, new stuff can't be too much above TeV scale

The Naturalness Connection

- Generically, solutions to naturalness involve new particles, which lead to deviations in Higgs couplings



MSSM light stops generically contribute (no mixing):

$$\kappa_g^2 = \frac{\sigma(gg \to h)}{\sigma(gg \to h)\,|_{SM}} \sim 1 + \left(\frac{700\ GeV}{\tilde{m}_t}\right) 3\%$$

Target precision < 3%

SM Higgs predicted to be a 0^+ Scalar

- H has integer spin since it decays to two integer spin particles
- H cannot have spin-1 since $H \to \gamma\gamma$
- Spin-1 assignment disfavored by angular distributions of $H \to ZZ$
- With assumptions about couplings to vector bosons and fermions, H unlikely to be spin-2
- Spin-0, negative parity hypothesis disfavored
  - Excluded at 97.8% (ATLAS) and 99.8% cl (CMS)

Look for Different CP Admixtures

- Example: angular correlations in h➔ZZ*

$$A \sim \epsilon_1^\mu \epsilon_2^\mu (a_1 g_{\mu\nu} M_Z^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta) = A_1 + A_2 + A_3$$

  - SM Higgs at LO, a_1=1,a_2=a_3=0
  - A_3 is CP odd
  - Look for CP odd component: $f_{a3} = \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$
  - CMS in h ➔ZZ*:
    - f_{a3} <0.56 at 95% cl ➔.13 (300 fb^{-1}), .04 (3000 fb^{-1})
- e^+e^- machines will do very well in e^+e^- ➔Z*➔ Zh
  - √S=500 (500 fb^{-1}) ➔ f_{a3}< 10^{-4}

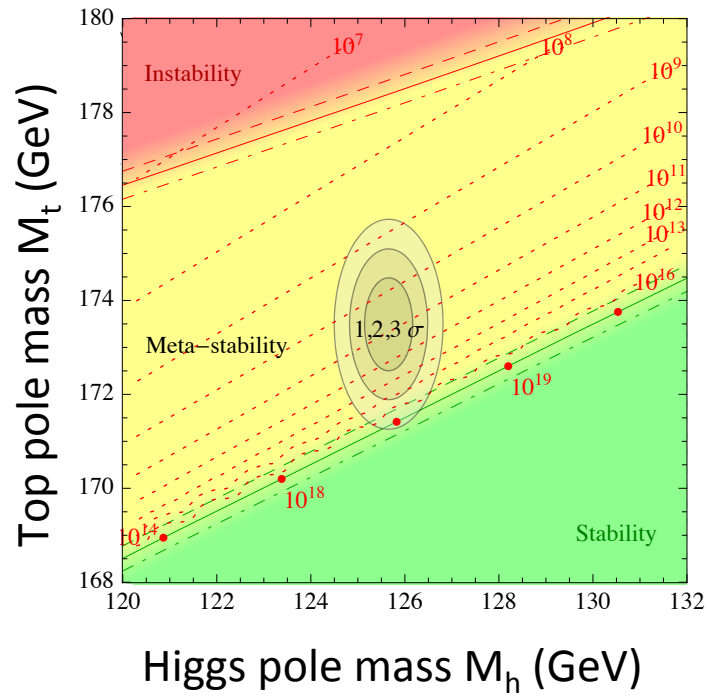
Mass Measurement

- The Higgs sector is perturbative $\lambda = \frac{M_h^2}{2v^2}$

$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4$$

$$\lambda \sim .13, \mu \sim 90\ GeV$$

- We can sensibly calculate to high scales
  - *Assuming no new physics!*
- Is M_h=125-126 GeV special?



[Buttazzo et al, 1307.3536]

Does Higgs Mass Matter?

- M_h important for M_W-M_t correlation, global fits
  - Consistency check of SM
- Check of predictions of BSM physics
- LHC: 300 (3000) fb^{-1} → ΔM_h~100 (~50) MeV
- ILC250, ΔM_h~35 MeV
- Muon collider gets precision from s-channel scan: ΔM_h~.06-.12 MeV (for beam energy resolution .003%-.01%)

$$\boxed{\begin{aligned} ATLAS: M_h &= 125.5 \pm 0.2_{stat} \pm 0.6_{sys}\ GeV \\ CMS: M_h &= 125.7 \pm 0.3_{stat} \pm 0.3_{sys}\ GeV \end{aligned}}$$

The Future

- An exciting precision program of understanding Higgs properties as a window to high scale physics
  - Couplings
    - Needed precision model dependent but ~ < 5%
    - Include couplings not predicted in SM
    - Exotic/rare decay channels
  - Mass/Width
  - Spin/parity
  - Searches for extended Higgs sectors
    - Complementary to precision coupling measurements

THIS IS NOT A SUMMARY OF THE HIGGS REPORT. IT IS MEANT TO GIVE THE FLAVOR OF MANY POSSIBILITIES. APOLOGIES FOR OMISSIONS